Photon-Counting Kilohertz Laser Ranging

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Who is building kHz systems?

- **USA**
  - NASA SLR2000 system proposed at 1994 Canberra Workshop
  - Development begun in late 1997
  - Field testing of prototype underway. No satellite ranging attempts yet
  - 2 kHz, 300 psec, 130 μJ transmitter; microchip laser oscillator plus multipass amplifier
- Austria
  - Presented at 2002 Washington DC Workshop
  - Uses existing Graz SLR station
  - 1-2 kHz, 10 psec, 500 μJ transmitter planned; SESAM oscillator plus multiple amplifiers
  - Near 100% return rate from LEO's with 80 μJ at 125 Hz (computer-limited)
- Australia, Japan, and Russia are experimenting with 100 Hz systems

Advantages of kHz Systems

- **Can take advantage of microchip and SESAM laser technologies**
  - Simpler, more compact, and less expensive than modelocked lasers for picosecond pulse generation
  - Transmitter requires fewer amplifiers due to higher oscillator energies (up to tens of μJ for microchips vs nJ for modelocked lasers)
  - No electro-optic pulse selection or high voltages required
- **Increases number of range returns per normal point by about two orders of magnitude**
  - Can improve normal point precision by over an order of magnitude relative to current 5 or 10 Hz systems
  - May allow meaningful two color measurements of differential atmospheric delay using high speed PMT's or SPADS
- **Improves single photon ranging statistics**
  - higher repetition rate compensates for single pulse photon deficit
  - Allows single pulse output flux to be reduced to eyesafe levels thereby eliminating the need for safety observers or aircraft radars
  - Single photon range measurements are free of signal amplitude biases
  - Orbit range residuals can reproduce the impulse response of the overall system (laser, satellite,detector) within a single normal point period

Special requirements of kHz systems

- KHz gating circuits and range gate generators
- Use of event timers rather than time interval units due to multiple pulses in flight
- More sophisticated ranging software required to extract the signal from the background noise and to link the proper return signal to each start pulse and compute the pulse time of flight
- Faster interfaces between the ranging hardware and system CPU
- More aggressive background noise reduction and fast receiver recovery times in the case of photon-counting systems

Computation of normal points from kHz photon-counting data

1. Create station impulse response *h(t-t')* histogram using most recent single cube calibration target data where t is the independently measured roundtrip transit time to the target (tracks changes in system calibration)
2. Convolve cal data with theoretical averaged impulse response of target (relative to the satellite CofM) to form Poisson generating function for each station/satellite combination, i.e.,

$$g(t) = h(t) \quad s(t)$$

3. Maximize convolution integral with the normal point residuals *r(t)* from the nominal orbital fit to compute the displacement of the normal point relative to the fit, i.e.,

$$\square t_{opt} = \max\left[r(t) \quad g(t)\right]$$

4. **or** compute centroids for 2 and 3 using current normal point algorithms and difference the results to obtain the displacement.

Impact on ILRS Data System

- The computation of the normal point can be carried out at the stations or by the analysts (TBD)
- The proper satellite center-of-mass correction to be applied by the analysts is the distance between the computed ground system-dependent centroid of *g(t)* and the satellite center of mass plus Δt_{opt}.
- If N is the number of ranges per normal point, the RMS uncertainty in the normal point should be given by

$$RMS_N = \frac{RMS\left[g(t)\right]}{\sqrt{N}}$$

- To the analyst, normal points from kHz systems should look identical to those from lower rate systems, but we may want to redefine the normal point integration times for each satellite to better support atmospheric modeling studies and multi-wavelength systems.

Example: SLR2000 Ranging to LAGEOS

•There are 240,000 (120 sec x 2 kHz)ranging attempts in a two minute LAGEOS normal point.

• For standard clear atmosphere (visibility = 23 km) and no cloud cover, about 5,000 ranges per normal point (2% return) are expected during acquisition at 20^{o} elevation and rising to a maximum of about 60,000 ranges (25% return) near zenith

•Since RMS of LAGEOS impulse response is about 15 mm, the RMS precision of the centroid (normal point) would have a lower limit of 0.2 mm during acquisition and 0.05 mm near zenith.This calculation ignores any statistical broadening due to the system impulse response or the minimum timing resolution of the receiver.